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Metrological research of a reference installation based on a high-pressure vessel

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Abstract

The urgency of development and metrological research of reference installations based on high-pressure vessels, which meet the requirements of the implementation of traceability of instruments for measuring gas volume and gas volume flow rate, is considered. The operation algorithm of the specified reference installations when transferring the unit of gas volume to the gas meters under consideration is studied. Based on the algorithm and features of the operation of PVTt-type standards, a list of the analysed uncertainties of type A is formulated when estimating the volume of the calibrated high-pressure vessel; when measuring the absolute pressure and absolute temperature of gas due to the influence of instability of pressure and temperature on the gas meter under consideration due to the presence of a temperature gradient in the vessel. Uncertainties of type B, which are determined by metrological characteristics of measuring instruments, as well as the uncertainty of parameters evaluated by means of calculation, in particular the compressibility factor of the working environment, the influence of water vapour on the working environment and the influence of the discreteness of the device for collecting information about measurements from the gas meter are considered.

Formulas to quantify the combined uncertainty of measuring the volume of the calibrated vessel, the absolute pressure and absolute temperature as well as to calculate the air compressibility factor for the operating conditions of the installation are given. These parameters are the absolute pressure and absolute temperature of the gas and the compressibility factor of the working environment in the vessel at the beginning and at the end of the reproduction of the reference volume as well at the inlet of the gas meter. The expressions for calculating the combined and expanded uncertainties of PVTt-type standards are given.

Keywords: gas volume; reference installation; calibrated vessel; gas meter; pressure; temperature; compressibility factor; uncertainty.

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Introduction

The need to develop metrological research in the field of metrology of natural gas measurements determines the relevance of the study of metrological aspects of the operation of reference installations for measuring gas volume and gas volume flow rate. Taking into account the need for practical implementation of the traceability when measuring gas volume and gas volume flow rate, it is recommended to introduce more PVTt-type standards (standards based on high-pressure vessels) that can operate on air and natural gas [1]. Prospects of the implementation of reference installations of this type are confirmed by the project of the metrological centre in Boyarka (Ukraine) [2] as well as by the creation of primary standards of gas volume in France, Great Britain, Japan, Sweden, and other countries [3]. Therefore, it is important to develop a metrological model of PVTt-type, which is the purpose of highlighting the study results of this paper.

Main part

Theoretically, there are well-known operation algorithms for pressure vessels (PVTt-type), which involve the leakage of gas from the vessel through the test area with the gas meter (GM) under consideration and measurement of pressure and temperature in the vessel and before the GM. In this case, the leakage of gas from the vessel is carried out for a certain period time Δt, during which there is a decrease in pressure in the vessel from the value of p_1 to p_2.

The use of the basic equation of state of the real gas involves the implementation of the following algorithm for calculating gas volume flow rate through the GM [4]:

$$q = \frac{V_0}{\Delta t}\left(\frac{P_1}{T_1 \cdot Z_1} - \frac{P_2}{T_2 \cdot Z_2}\right)\frac{T_3 \cdot Z_3}{P_3}, \quad (1)$$

where q is the gas volume flow rate through the GM; V_0 is the volume of the calibrated vessel; Δt is the time of gas volume flow rate through the GM; P_1, T_1, Z_1;

P_2, T_2, Z_2; P_3, T_3, Z_3 are the absolute pressure, absolute temperature and compressibility factor of the gas in the vessel at the beginning and at the end of the gas leakage and in the test area before the GM, respectively.

Assuming a stable value of the reproducible gas volume flow rate q, the formula for determining the reference volume of V_{GM} gas passing through the meter will be as follows:

$$V_{GM} = q \cdot \Delta t. \tag{2}$$

Substituting (1) into (2) we obtain:

$$V_{GM} = V_0 \left(\frac{P_1}{T_1 \cdot Z_1} - \frac{P_2}{T_2 \cdot Z_2} \right) \cdot \frac{T_3 \cdot Z_3}{P_3}. \tag{3}$$

The metrological model based on the theory of uncertainty contains standard uncertainties of types A and B, which in combination will form the combined and expanded uncertainties of the installation [5].

Uncertainties of type A are determined by the parameters to be experimentally examined during metrological studies, in particular: the volume of the calibrated high-pressure vessel; gas pressure, gas temperature; instability of pressure and temperature before the GM; the presence of a temperature gradient in the vessel.

Uncertainties of type B are formed by the standard uncertainties of the used measuring equipment, as well as by the uncertainty of the parameters determined by means of calculation, in particular, the compressibility factor of the working environment. Moreover, an additional methodological error may be the presence of water vapour in the working environment and the discreteness of the device for collecting information about measurements from the GM.

With the participation of the authors, several technical improvements of this type of standards are suggested, which allows to increase their accuracy and reduce the components of uncertainty. For example, to reduce the temperature gradient in the vessel, according to the patent [6], it is suggested to use an assembly for axial swirling of the gas volume flow rate when supplying gas to the vessel. To reduce the error of the installation due to the instability of pressure and temperature before the GM, according to the patent [7], together with the constructive improvement of the information and measuring system of the installation, it is suggested to improve control devices for stabilizing dynamic gas parameters before the GM under consideration. Also according to [7], to reduce the error due to the presence of water vapour in the working environment, it is advisable to additionally equip the gas supply line with a gas dehumidifier.

Therefore, to develop a model for calculating the uncertainty of measurements, we will focus on the methodological study of the algorithm for transferring the unit of gas volume, given by formula (3), provided the installation operates in the air.

To evaluate the combined and expanded uncertainty of the reference volume of V_{GM} gas passing through the meter under consideration, the uncertainties of all constituent quantities included in expression (3) should be evaluated in advance.

Let us consider the uncertainty of measuring the volume of the calibrated vessel V_0.

The uncertainty of type A is evaluated by expression [5]:

$$u_A(V_0) = \sqrt{\frac{\sum_{i=1}^{n} \left(V_{0i} - \overline{V_0} \right)^2}{n(n-1)}}, \tag{4}$$

where V_{0i} is the volume of the calibrated vessel during the i-th measurement; $\overline{V_0}$ is the arithmetic mean of the volume of the calibrated vessel for n measurements.

The uncertainty of type B is formed by metrological characteristics of the used measuring instruments. At the same time, the uniform law of the distribution of measurement results is accepted. Therefore, the uncertainty will be evaluated by expression [5]:

$$u_B(V_0) = \frac{\delta_{V_0}}{\sqrt{3}}, \tag{5}$$

where δ_{V_0} is the maximum permissible error of the reference meter of the liquid used to calibrate the vessel V_0.

The combined uncertainty of the calibrated vessel volume measurement is determined as follows [5]:

$$u_C(V_0) = \sqrt{u_A(V_0)^2 + u_B(V_0)^2}. \tag{6}$$

The evaluation of combined uncertainties of the results of measuring the absolute pressure in the vessel at the beginning and at the end of the gas leakage before the GM, P_1, P_2, P_3 accordingly, and the uncertainties of measuring the temperature in the vessel $u_C(T)$ at the beginning and at the end of the gas leakage before the GM, T_1, T_2, T_3 accordingly, is carried out similarly by algorithm (4) – (6).

To evaluate the uncertainty of the calculation of the compressibility factor of the gas in the vessel at the beginning Z_1 and at the end of the gas leakage Z_2 and before the GM Z_3, the uncertainty of type B should be evaluated, as this coefficient is determined by means of calculation and not by measurement results.

According to [4, 8] the following approximation dependence can be used to determine the gas compressibility factor:

$$Z = 0.99963 - P(0.045955 - 0.000141 \cdot T), \tag{7}$$

where P and T are the absolute pressure and absolute temperature of the air in the installation.

Therefore, the component of the combined uncertainty will be the uncertainty from the approximation of the dependence (7).

Let us consider the method of evaluating the uncertainty of the compressibility factor of the gas Z_1 in the vessel at the beginning of the gas leakage.

To evaluate the uncertainty of the gas compressibility factor, the expressions for estimating the weight coefficients of the components included in (7) should be defined. In particular, at the beginning of the gas leakage at absolute pressure P_1 and absolute temperature T_1 in the vessel we obtain:

$$\frac{\partial Z_1}{\partial P_1} = 0.000141 \cdot T_1 - 0.045955; \tag{8}$$

$$\frac{\partial Z_1}{\partial T_1} = 0.000141 \cdot P_1. \tag{9}$$

The combined uncertainty of determining the compressibility factor of the gas Z_1 in the vessel at the beginning of the gas leakage is as follows

$$u_C(Z_1) = \sqrt{\left(\frac{\partial Z_1}{\partial P_1} u_C(P_1)\right)^2 + \left(\frac{\partial Z_1}{\partial T_1} u_C(T_1)\right)^2 + u_{apr}^2}, \tag{10}$$

where $u_C(P_1)$ and $u_C(T_1)$ are the combined uncertainties of the result of measuring the absolute pressure P_1 and absolute temperature T_1 at the beginning of the gas leakage, respectively; u_{apr} is the uncertainty of the approximation of expression (7).

Evaluation of the uncertainty of gas compressibility factors Z_2 and Z_3 under operating conditions of the installation is carried out similarly by algorithm (7) – (10).

When evaluating the combined uncertainty of the volume of V_{GM} gas that passing through the meter, we write expressions to estimate the weight coefficients of the components included in (3):

$$\frac{\partial V_{GM}}{\partial V_0} = \left(\frac{P_1}{T_1 \cdot Z_1} - \frac{P_2}{T_2 \cdot Z_2}\right) \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{11}$$

$$\frac{\partial V_{GM}}{\partial P_1} = \frac{V_0}{T_1 \cdot Z_1} \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{12}$$

$$\frac{\partial V_{GM}}{\partial T_1} = -\frac{V_0 \cdot P_1}{T_1^2 \cdot Z_1} \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{13}$$

$$\frac{\partial V_{GM}}{\partial Z_1} = -\frac{V_0 \cdot P_1}{T_1 \cdot Z_1^2} \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{14}$$

$$\frac{\partial V_{GM}}{\partial P_2} = -\frac{V_0}{T_2 \cdot Z_2} \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{15}$$

$$\frac{\partial V_{GM}}{\partial T_2} = \frac{V_0 \cdot P_2}{T_2^2 \cdot Z_2} \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{16}$$

$$\frac{\partial V_{GM}}{\partial Z_2} = \frac{V_0 \cdot P_2}{T_2 \cdot Z_2^2} \cdot \frac{T_3 \cdot Z_3}{P_3}; \tag{17}$$

$$\frac{\partial V_{GM}}{\partial P_3} = \frac{V_0 \cdot T_3 \cdot Z_3}{P_3^2} \cdot \left(\frac{P_2}{T_2 \cdot Z_2} - \frac{P_1}{T_1 \cdot Z_1}\right); \tag{18}$$

$$\frac{\partial V_{GM}}{\partial T_3} = \frac{V_0 \cdot Z_3}{P_3} \cdot \left(\frac{P_1}{T_1 \cdot Z_1} - \frac{P_2}{T_2 \cdot Z_2}\right); \tag{19}$$

$$\frac{\partial V_{GM}}{\partial Z_3} = \frac{V_0 \cdot T_3}{P_3} \cdot \left(\frac{P_1}{T_1 \cdot Z_1} - \frac{P_2}{T_2 \cdot Z_2}\right). \tag{20}$$

The combined uncertainty, when the installation operates in the mode of reproduction of the volume, taking into account the main provisions of the theory of the uncertainty in measurements [5], is calculated by the formula:

$$u_C(V_{GM}) = \sqrt{\begin{aligned} &\left(\frac{\partial V_{GM}}{\partial V_0} \cdot u_C(V_0)\right)^2 + \left(\frac{\partial V_{GM}}{\partial P_1} \cdot u_C(P_1)\right)^2 + \left(\frac{\partial V_{GM}}{\partial T_1} \cdot u_C(T_1)\right)^2 + \left(\frac{\partial V_{GM}}{\partial Z_1} \cdot u_C(Z_1)\right)^2 + \\ &+\left(\frac{\partial V_{GM}}{\partial P_2} \cdot u_C(P_2)\right)^2 + \left(\frac{\partial V_{GM}}{\partial T_2} \cdot u_C(T_2)\right)^2 + \left(\frac{\partial V_{GM}}{\partial Z_2} \cdot u_C(Z_2)\right)^2 + \\ &+\left(\frac{\partial V_{GM}}{\partial P_3} \cdot u_C(P_3)\right)^2 + \left(\frac{\partial V_{GM}}{\partial T_3} \cdot u_C(T_3)\right)^2 + \left(\frac{\partial V_{GM}}{\partial Z_3} \cdot u_C(Z_3)\right)^2 \end{aligned}}. \tag{21}$$

Expanded uncertainty is calculated by the formula:

$$U_P(V_{GM}) = k_0 \cdot u_C(V_{GM}), \tag{22}$$

where k_0 is the coverage factor that forms the numerical value of the expanded uncertainty for the corresponding selected confidence probability [5].

Conclusion

Based on the results of theoretical research, the algorithms to calculate the standard uncertainties of calibration of the reference vessel, measure gas pressure and temperature, and calculate the gas compressibility factor, which is necessary for metrological assessment of the reference installation based on the high-pressure vessel.

The expressions for calculating the combined and expanded uncertainties of the installation under consideration are given.

The use of numerical modelling characterizes that the expanded uncertainty of the installations with the correct choice of reference tools and measuring transducers can be within ± (0.25... 0.45)%, which justifies the possibility of their use as working standards.

Метрологічні дослідження еталонної установки на базі ємності високого тиску

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Анотація

Розглянуто актуальність розроблення і метрологічних досліджень еталонних установок на базі ємності високого тиску, які відповідають вимогам для засобів вимірювання об'єму та об'ємної витрати газу. Досліджено алгоритм функціонування вказаних еталонних установок при передаванні одиниці об'єму газу до досліджуваних лічильників газу. На основі алгоритму й особливостей функціонування установок PVTt-типу сформульовано перелік досліджуваних невизначеностей типу А: при оцінюванні об'єму каліброваної ємності високого тиску; при вимірюванні абсолютного тиску та абсолютної температури газу; від впливу нестабільності тиску і температури перед досліджуваним лічильником газу; від наявності градієнта температури в ємності. Розглянуті невизначеності типу В, які визначаються метрологічними характеристиками засобів вимірювальної техніки, а також невизначеністю параметрів, що оцінюються розрахунково, зокрема фактор стисливості робочого середовища, вплив від наявності водяної пари в робочому середовищі, вплив дискретності пристрою збору вимірювальної інформації з лічильника газу.

Подані формули для кількісної оцінки сумарної невизначеності вимірювання об'єму каліброваної ємності, абсолютного тиску й абсолютної температури, а також розрахунку фактора стисливості повітря для робочих умов установки. Такими параметрами є абсолютний тиск і температура газу та фактор стисливості робочого середовища в ємності на початку і в кінці відтворення еталонного об'єму, а також ці параметри на вході лічильника газу. Наведені вирази для обчислення сумарної та розширеної невизначеностей установок PVTt-типу.

Ключові слова: об'єм газу; еталонна установка; калібрована ємність; лічильник газу; тиск; температура; фактор стисливості; невизначеність.

Метрологические исследования эталонной установки на базе емкости высокого давления

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Аннотация

Рассмотрена актуальность разработки и метрологических исследований эталонных установок на базе емкости высокого давления. Исследован алгоритм функционирования указанных эталонных установок при передаче единицы объема газа к исследуемым счетчикам. С учетом алгоритма и особенностей функционирования установок PVTt-типа сформулирован перечень неопределенностей типа А и В. Представлены формулы для количественной оценки суммарной неопределенности измерения объема калиброванной емкости, абсолютного давления и абсолютной температуры, а также расчета фактора сжимаемости воздуха для рабочих условий установки. Такими параметрами являются абсолютное давление и температура газа, фактор сжимаемости рабочей среды в емкости в начале и в конце воспроизведения эталонного объема, а также эти параметры на входе счетчика газа. Представлены выражения для вычисления суммарной и расширенной неопределенностей установок PVTt-типа.

Ключевые слова: объем газа; эталонная установка; калиброванная емкость; счетчик газа; давление; температура; фактор сжимаемости; неопределенность.

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